Rev. Inst. Med. Trop. Sao Paulo
54(4):179-191, July-August, 2012
doi: 10.1590/S0036-46652012000400001

REVIEW

IMPACT OF DAMS AND IRRIGATION SCHEMES IN ANOPHELINE (DIPTERA: CULICIDAE) BIONOMICS AND MALARIA EPIDEMIOLOGY

Jordi SANCHEZ-RIBAS(1,3), Gabriel PARRA-HENAO(2) & Anthony Érico GUIMARÃES(3)

SUMMARY

Irrigation schemes and dams have posed a great concern on public health systems of several countries, mainly in the tropics. The focus of the present review is to elucidate the different ways how these human interventions may have an effect on population dynamics of anopheline mosquitoes and hence, how local malaria transmission patterns may be changed. We discuss different studies within the three main tropical and sub-tropical regions (namely Africa, Asia and the Pacific and the Americas). Factors such as pre-human impact malaria epidemiological patterns, control measures, demographic movements, human behaviour and local *Anopheles* bionomics would determine if the implementation of an irrigation scheme or a dam will have negative effects on human health. Some examples of successful implementation of control measures in such settings are presented. The use of Geographic Information System as a powerful tool to assist on the study and control of malaria in these scenarios is also highlighted.

KEYWORDS: Malaria transmission; *Anopheles* bionomics; Water development project; Control.

INTRODUCTION

As a result of human expansion through the world and environmental modifications to satisfy our necessities, new interactions between us and the environment have emerged, leading to new epidemiological patterns of the main vector-borne diseases[63]. Mainly in Africa, Asia and the Pacific and the Americas, irrigation schemes and dams have extensively proliferated to cover the growing food and energetic demands of these regions[99]. It is estimated that a total of 18,3 million people live within 2 km of the shoreline of a dam and other 851,3 million people inhabit areas in close proximity to irrigation schemes in malaria-endemic areas[49].

Although not always the case, there is growing evidence that demographic movements coupled with environmental alterations may favour the proliferation of vector-borne diseases, the main ones being malaria, lymphatic filariasis, Japanese B encephalitis and onchocerciasis[42]. Over these diseases, malaria poses the major threat to public health, with approximately 190 and 311 million clinical cases per year, and accounting for between 708,000 and 1,003,000 deaths annually, mainly in sub-Saharan Africa[15]. The high adaptability of some malaria vectors, control program problems such as difficulties in implementation, financial sustainability and poor population adherence to control measures coupled with other factors outside of the health sector, constitute a threat to public health in water development projects (WDP) of many developing countries[60]. For these reasons, we chose irrigation schemes and dams and their effect on *Anopheles* population dynamics and malaria transmission as the focus for this review.

SEARCH STRATEGY

We searched for articles mostly through PubMed using key words such as "malaria", "*Anopheles*", "dams", "irrigation schemes", "environmental impact", "ricefields". A critical selection of informative studies was made and extra references were included from World Health Organization (WHO) publications and various online resources and books on *Anopheles* and malaria. Seventy-one studies published presenting original data in international peer-reviewed journals were included. Also, we considered for this publication ten previous reviews on the topic of modified environments and their effect on malaria epidemiology.

Different types of study design exist to evaluate the impact of WDP on malaria. The best approach to characterize their direct effect is provided by studies that compare data on *Anopheles* bionomics or malaria transmission before and after human intervention. However, these types of studies are not the most common, due to limitations such as the absence of reliable information on the pre or post intervention scenario. An alternative approach is to compare the prevalence or incidence of malaria between communities under WDP influence and others nearby,

(1) Laboratório de Imunoparasitologia, Instituto Oswaldo Cruz/FIOCRUZ, Rio de Janeiro, RJ, Brazil. E-mail: jordi@ioc.fiocruz.br
(2) Programa de Biología – Instituto Colombiano de Medicina Tropical, Universidad CES. E-mail: gparra@ces.edu.co
(3) Laboratório de Diptera, Instituto Oswaldo Cruz/FIOCRUZ, Rio de Janeiro, RJ, Brazil. E-mail: anthony@ioc.fiocruz.br
Correspondence to: Jordi SANCHEZ-RIBAS. E-mail: jordi@ioc.fiocruz.br

used as controls. The latter must present similar characteristics to the former to validate these comparisons and minimize the effect of confounders. Although less conclusive, a third alternative is to use only post-intervention data, and compare it to other parts of the country. All three study designs were considered in this review.

WATER DEVELOPMENT PROJECTS AND MALARIA

Malaria manifestations in each community, region or country are defined by the interaction in time and space of intrinsic (human, parasite and mosquito) and extrinsic (environmental and socio-economical conditions, human behaviour and control measures) determinants of the disease[11]. For example, population relocations into new areas of irrigation or dam construction can draw two types of scenarios with different epidemiological significance. Firstly, there could be an introduction of *Plasmodium* parasites into free-malaria areas by immigrant workers coming from other endemic regions and secondly, non-immune populations could be exposed to malaria after moving into transmission areas[43]. Due to the high complexity of the factors that modulate malaria transmission, it is necessary to conduct site-specific studies to research on the contextual determinants of the disease and hence consistently evaluate the impact that each WDP has on the local malaria epidemiological pattern.

DAMS

With the discovery of the turbine in 1832, the era of the big dams constructed mainly for hydropower generation started, triggering the construction of mega-dams during the 1930s. The majority of the rivers have been dammed and hydropower energy represents the 13% of the total electrical power generated in USA, 99% in Norway, 75% of New Zealand and 70% of Latin America[48]. Brazil, China, Colombia, India, Peru and Congo are the countries with the greatest hydroelectric potential unexploited, with the Amazon, Congo and Mekong basins being the ones that can be exploited best for this purpose[42]. 40,000 large dams and other 800,000 man-made lakes of smaller size were estimated to have been built by 2001[49].

AFRICA

When looking at the effect of WDP on malaria, it is important to establish if a stable or unstable transmission pattern in the area exists. This factor will determine, to a great extent, if the WDP will have a positive or negative effect, or no effect at all, on malaria incidence. Stable malaria transmission areas are characterised by high infant mortality and also high levels of acquired immunity due to the vast levels of disease exposure. In these areas, transmission levels are high and without marked fluctuations in incidence over time. In contrast, areas with irregular transmission between months and years and with markedly lower transmission rates are classified as unstable. In such epidemiological settings, epidemics are common and all age groups may be evenly affected, resulting from the lower acquired immunity of these populations[16].

Human environmental modifications normally exert a great impact on unstable areas, most of the times in form of epidemics with high morbidity and mortality rates[61]. Nevertheless, this is not always the case, like in the Gleita dam constructed in an area of unstable malaria transmission of Mauritania, where the malaria incidence was not enhanced[6]. On the other hand, stable areas sustain the capacity to better absorb the artificial alterations, resulting in small effects on the per se very high malaria exposure[61].

Anopheles gambiae s.s, *An. arabiensis* (both pertaining to the same species complex) and *An. funestus* are considered the three main malaria vectors in sub-Saharan Africa. The members of the gambiae complex have been recorded extensively both in man-made lakes and flooded ricefields. The presence of *An. funestus* in such artificially altered environments has been less studied. However, the occurrence of this species in flooded paddy fields may be expected, as its larvae have been associated with permanent breeding sites with emerging vegetation[32].

Pre- and post-intervention data demonstrated that the construction and operation of two large dams in the Senegal River, increased anopheline densities but without exerting any significant influence on malaria transmission. This could be explained because exacerbated mosquito densities were not accompanied by favourable conditions to allow the female mosquitoes to live long enough to become infected, permit the complete *Plasmodium* development cycle to take place inside them and transmit the disease to another susceptible host[18].

Although much attention has been given to large dams (defined as having more than 15 meters high or more than three million m^3 of water storage capacity[49]) it is highly probable that small dams may pose a greater impact on malaria transmission. These "micro-dams" are developed at much greater rate and their surveillance and control is more difficult when compared with the big projects[60]. The shoreline of a man-made lake is considered the main mosquito producing area. For this reason, a group of small dams will have a total shoreline length much more extensive than a unique big dam, but with the equivalent water surface. So, micro-dams will have a higher potential for mosquito production and may become an important source of health risk[90]. The region of Tigray in northern Ethiopia constitutes a prime example of the effect of micro-dams in exacerbating malaria incidence in an unstable transmission area. Communities in the vicinity of the micro-dams presented a seven fold higher transmission rate than control villages. This increase was of special concern because before the implementation of the micro-dams, low transmission levels existed in the area, and thus low acquired immunity levels in the local population also existed[29]. More examples of impoundments and malaria are found in Ethiopia. For example, the construction of the Koka dam was also associated with increased levels of malaria transmission and with *P. falciparum* becoming more prevalent in communities adjacent to the dam site[55]. Similarly, YEWHALAW *et al.*[101] observed a higher proportion of *P. vivax* infections on children living in communities near the Gilgel-Gibe dam, but the proportions of *P. falciparum* cases were not significantly different for at-risk communities and villages farther away. Finally, transmission enhancement was also verified in communities close to the Bamendjin dam in Cameroon[3].

ASIA AND THE PACIFIC

Some reports demonstrate how dam construction can exert influence on increasing malaria transmission levels in Asia. The Bargi dam is a well documented example of this case, which facilitated a malaria epidemic in 1996 with high mortality rates and increased proportion of *P. falciparum* infections[81]. Also in India, the Sardar Sarovar artificial lake favoured a sharp increase in malaria transmission[80].

In contrast with the case of the micro-dams in the Tigray region of Ethiopia, similar small-WDP was associated with an amelioration of malaria in the Orissa region of India. Pre-intervention surveys yielded 1304 cases per 1000 people/year and after the implementation of the micro-dams this index dropped to 181.1 cases per 1000 people/year. In this area the main vector was *An. fluviatilis*, a highly antropophilic species and with preference to breed in slow flow streams. The construction of small dams impeded the natural flow of the streams, thus converting the area in an inhospitable breeding ground for this vector[76].

In the neighbouring Bangladesh, an unstable malaria transmission pattern exists, with *P. vivax* being the predominant parasite species and transmitted by the local malaria vector, *An. philippinensis*. With the construction of several dams for flood control of the lowland areas the abundance of this vector diminished steadily and, consequently, the risk of acquiring malaria also diminished. This phenomenon could be explained by the direct removal of natural breeding sites and by the high concentrations of organic matter of the new water bodies, factors that normally prejudice *Anopheles* proliferation[9].

In Southeast Asia, dams and irrigation schemes have been extensively implemented. Intense deforestation aimed to implant these projects led to the marked reduction of the highly efficient forest malaria vector *An. dirus*. However, some of these new scenarios were well colonized by another local efficient vector, *An. minimus*[60]. The Srinagarind dam is one of the few examples that documented the effect of a dam on malaria in this region. *An. minimus*, *An. balabacensis* and *An. maculatus* thrived in this new artificial water body, resulting in transmission enhancement[12].

LATIN AMERICA

The Amazon is vast and ecologically very complex, comprising an irregular distribution of malaria prevalence, with the highest indices usually concentrated in settlements of frontier areas. Environmental alterations due to diverse human activities and asymptomatic parasite carriage have been postulated as the two major factors implied in the maintenance and recrudescence of malaria transmission in this huge tropical region[77]. In the Neotropics, most studies relating dams and malaria have been carried out in Brazil, which possesses one of the biggest hydroelectrical potentials in the world, as most of the Amazon basin is contained within its borders. The Brazilian electrical system is largely sustained by hydropower generating dams which may disrupt the ecological equilibrium in many areas, directly affecting human health. Brazilian dams are good examples of WDP that have mobilized a big amount of people that are placed at the dam construction sites in precarious settlements, where they may stay for several years during the reservoir construction. This demographic pressure may directly modify the local physical and biotical environments, thus producing new epidemiological risks factors[36]. *An. darlingi*, *An. albitarsis s.l*, *An. aquasalis, An. nuneztovari* and *An. triannulatus s.l* have been encountered in Brazil naturally transmitting human *Plasmodium* parasites in areas under a WDP influence[37,78].

In Latin America, most of the man-made lakes have been associated with a worsened health status of the at-risk communities, mainly due to a recrudescence of some vector-borne diseases[90]. The Balbina, Itaipu and Serra da Mesa dams in Brazil are good examples of the effect of dams on malaria. Although malaria does not pose such a major public health problem like in others parts of Africa and Asia, in the Americas WDP may exert a more profound effect on the determinants of the disease[49].

The construction of man-made lakes is normally associated with a decline of the mosquito diversity, favouring only those species that can adapt to the new artificial environments. In the Balbina dam the opposite effect occurred, with 11 anopheline species reported after five years of the filling of the reservoir compared with only two species found during the pre-intervention surveys. *An. darlingi* and *An. nuneztovari* were found naturally infected with *Plasmodium* parasites[65]. Still in Brazil, *An. darlingi* was also found to be the predominant species in the influence area of the Porteira and Porto Primavera dams and in the area where the future Madeira dam will be constructed[7,17,34,88].

The Itaipu dam is one of the best documented cases where the combination of demographic, epidemiological and entomological factors brought back malaria transmission in an area where it was under control[37,89]. Before the reservoir construction malaria transmission was almost inexistent in the area. In the 70s a big contingent of people from Paraná (the southern Brazilian State where the dam was planed) moved to other states of the legal Amazon, looking for a better future. Defeated by the hard living conditions of their new settlements, they eventually came back to Paraná, some of them introducing new *Plasmodium* parasite strains in the area under the influence of the Itaipu dam. *An. darlingi* populations had been favoured by the new breeding opportunities of the impoundment and this efficient vector entered in contact with the returning infected people, resulting in 3000 malaria cases between 1989 and 1992. *An. albitarsis s.l* and *An. galvaoi* were also appointed as vectors with epidemiological relevance in this area[22,37].

A similar situation occurred in the Serra da Mesa dam in Brazil, where human intrusion, followed by environmental changes that altered vector biology, also resulted in increased malaria incidence. Once more, *An. darlingi* was appointed as the principal factor responsible for sustaining the malaria transmission in the reservoir area. In this case, the importance of *An. albitarsis s.l* as a vector was again highlighted due to its high capacity of adaptation to human made environments[36]. *An. albitarsis s.l* densities were also increased when the Taquaraçu and Rosal dams were completed, both in Brazil[67,90].

IRRIGATION SCHEMES

Very old observations already associated rice-harvested areas with malaria. For example, in 1489 rice production was outlawed in Spain, while in Portugal, the Czech Republic and North America, paddy fields were thought to be associated with the increase of malaria during the XVII century[50,75]. Overall, few studies that compare malaria incidence before and after an irrigation scheme is implanted have been consistently reported. Paddy fields are usually introduced in soils with a greater capacity to retain water. So, it is probable that communities where irrigations schemes have been established already had a higher transmission levels than control ones, making it more difficult to conduct reliable post-intervention comparisons[44].

Irrigation systems represent the 75% of the total rice production and are the most useful approach to allow the culture of this crop in areas of irregular rainfall patterns and arid and semi-arid regions, apart from increasing the number and the productivity of crop cultures per year[50]. In order to meet the growing food demand, a 70% increase in global rice production is estimated within the next 25 years, with most of the production expected in developing countries[73]. Nevertheless, rice flooded fields result in habitat simplification, an exacerbated number of potential breeding sites due to a higher availability of water bodies and microclimate modifications. These are factors that may induce the proliferation of certain anopheline species[1]. For example, due to high humidity levels in irrigated fields, the local Egyptian malaria vector, *An. pharoensis*, lengthened its longevity[73].

AFRICA

Only around 8.5% of African agricultural production is under irrigation systems, but this tendency is expected to increase steadily in the coming years. Almost half of Africa is too dry to rely only in rainfall for agricultural purposes, so irrigation is the best approach to convert arid and semi-arid land extensions in productive areas. There is a clear overlapping distribution between the main malaria vectors and the potential areas for irrigation cultivation[44,50].

Various reports related irrigated agro-ecosystems with an exacerbated malaria burden, sometimes changing the transmission patterns from seasonal to perennial or increasing the degree of endemicity. In paddy fields of the Rusizi area in Burundi, a sharp increase in *P. falciparum* malaria cases was related with a higher production of *An. arabiensis* in the flooded fields[10]. DIUK-WASSER *et al.*[19] showed that irrigation schemes also increased the densities of *An. gambiae s.s* in Mali, mainly during the early crop stages. In this example, the effect of the irrigated crops on malaria was different depending on the dry (increased transmission) or wet season (curtailed transmission). In Sierra Leone, an area under irrigation was occupied by lots of people escaping from other endemic areas under conflict. The introduction of parasites plus the presence of local competent vectors conduced again to a worsened public health situation[26]. Similarly, in rice-growing areas of the Gezira-Managil scheme in Sudan, the combination of increased densities of *An. arabiensis* and the arrival of people from other neighbouring endemic areas, resulted in an exacerbated malaria burden and the change of the malaria transmission pattern from seasonal to perennial[21]. This phenomenon was also verified in the Manantali dam influence area in Mali[47]. In areas proximal to an irrigation scheme in Cameroon, high densities of *An. arabiensis* and *An. gambiae s.s* accounted for an Entomological Inoculation Rate (EIR) of 0.82 infective bites/person/night. With crop maturation, *An. pharoensis* became more abundant and was also involved in malaria transmission[68].

MARRAMA *et al.*[58] conducted a study of the effect of irrigated ricefields in two areas with different epidemiological patterns in Madagascar, one sub-arid region (unstable transmission) and another tropical humid area (stable transmission). In the sub-arid region the EIR was 150 times higher (63 infective bites/person/year mainly due to *An. funestus*) in areas within the influence of the paddy fields when compared with farther away communities. In addition, the transmission pattern changed from seasonal to perennial, thus converting this area into a stable transmission focus inside an originally unstable transmission area. A similar situation occurred in unstable transmission areas of the Madagascar highlands, where irrigation projects favoured the proliferation of *An. funestus*, resulting in severe malaria epidemics[49]. In the tropical humid area the transmission was not increased due to paddy fields, and *An. mascarensis,* which is an endemic species to the island, was appointed as the primary vector[58].

Contrasting with the previous examples, not always flooded paddy fields have been associated with increased malaria transmission. IJUMBA & LINDSAY[44] depicted the situation where a marked increase of anopheline densities due to ricefields did not result in exacerbated malaria incidence. This phenomenon can be explained due to the better economic and social conditions of the communities living near the irrigation schemes, where more reliable health structures, better housing conditions and more resources to be spent in vector control and efficient treatments and preventive measures exist. This was verified in stable transmission areas of paddy fields in the Ivory Coast[40], Cameroon[4], and in northern Tanzania[45]. In the last example, although *An. arabiensis* densities were four times higher in irrigated areas, an EIR between 61 and 68% lower was observed. The authors surmised that this observation was in part because of the lower preference to take blood from human hosts.

Three factors explained why, in rice irrigated areas in Burkina Faso that recorded four times higher *An. gambiae s.l* densities, exacerbated malaria transmission was not recorded. Due to very high vector densities, an increased use of bednets reduced the contact rates between settlers and the mosquito fauna. Like in the case of the dams of the Senegal River, increased mosquito densities resulted in decreased survivorship, so the mosquitoes did not live long enough to allow the full parasite development inside them. Thirdly, it was suggested that nulliparous females were more anthropophilic than parous ones[10]. A similar situation happened in the irrigation scheme of Ahero in Kenya and in an irrigated sahelian sub-arid area of Mali, where high mosquito densities were coupled with lower mosquito survival rates and anthropophilia, resulting in lowered sporozoite rates and transmission of malaria[20,46].

ASIA AND THE PACIFIC

Several examples presented the negative health effects of irrigation schemes in this region. In Turkey, irrigated crops resulted in an increased population density of the local malaria vector *An. sacharovi*, which in association with the parasite introduction by workers coming from other endemic areas of the country, provoked in 1977 a severe epidemic of *P.vivax* with 101,867 recorded cases[35]. A very similar situation occurred in Afghanistan. In this case, *An. pulcherrimus* and *An. hyrcanus* were the local species to benefit from irrigated fields. Also, an introduction of parasites by people escaping from endemic conflict-stricken zones played an important role in the subsequent increase in *P.vivax* transmission[23].

Several examples of WDP and increased malaria transmission come from India. In the Punjab area, the transmission pattern was switched from seasonal to perennial due to irrigation fields. Higher humidity levels also increased mosquito longevity[74]. In the Asian region of the Thar Desert, *An. culicifacies* invaded newly implanted paddy fields, and subsequent *P. falciparum* epidemics started to occur in the area. *An. stephensi* had maintained low transmission levels in this area before irrigation. It was verified that this vector also adapted to spillages from irrigation canals. In another instance, *An. culicifacies* and *An. fluviatilis* invaded the irrigation areas along the Narmada river, changing the transmission pattern again from seasonal to perennial and with a malaria incidence 10-15 times higher[92]. Areas irrigated by the Bargi dam showed increased malaria incidence by four fold, but in this case, *An. annularis* was the predominant anopheline species[81]. This vector was also important for the occurrence of *P.vivax* infections in the irrigation scheme of Mahaweli in Sri Lanka. However, this secondary vector was not able to maintain the incidence at the same levels than when *An. culicifacies* was the main responsible for *Plasmodium* transmission in the same area during preceding rice developmental stages[1,2,66].

Irrigated fields promoted the proliferation of anopheline species and increased malaria transmission in other countries of Asia, such as China (*An. sinensis*), Indonesia (*An. aconitus* and *An. barbitorsis*) and Laos PDR (*An. nivipes* as the suspected vector)[52,75]. In another area of Indonesia, the forest species *An. umbrosus*, was substituted due to paddy fields implementation by the more efficient vector *An. campestris*, resulting in local malaria outbreaks[96].

LATIN AMERICA

Few studies have recorded the effect of irrigation schemes on malaria in this continent. In Central America, the main malaria vector *An. albimanus* was favoured by irrigation systems and concomitantly with the arrival of people from endemic areas, the risk for *P.vivax* infection was triggered. Increased densities of *An. albimanus*, *An. calderoni* and *An. pseudopunctipennis* were recorded in irrigation areas of an arid coastal region of Peru[70]. FORATTINI *et al.*[24,25] compiled information on the effect of ricefields on local *Anopheles* populations in the Vale da Ribeira in southeast Brazil. Their results revealed that *An. albitarsis s.l* was the species that proliferated more efficiently in these new environments. *An. aquasalis* was incriminated as a vector in irrigation areas of the British Guyenne[31].

Colonization schemes such as agricultural settlements in areas of the Amazon frontier, may also jeopardize the health of the local population[14]. For example, in the Jari irrigation scheme of the central Amazon basin, *An. darlingi* found excellent new breeding sites to prosper and thus, posed an increased risk for malaria transmission in the area[54]. Similarly, in the northern Amazon, BARROS *et al.*[5] verified that an agricultural settlement registered much more malaria cases than a neighbouring site without dams being used for crop production.

Anopheline mosquitoes may modify their behaviour to survive. A prime example was found in British Guyenne. In the coastal areas, *An. darlingi* and malaria were brought under control due to sound control methods. However, expansion of rice cultivation plus the arrival of people from endemic areas to work in the new water projects drew a new epidemiological scenario conducive for malaria transmission. With the reduction of livestock as well, the secondary vector *An. aquasalis*, which had been up to that moment highly zoophilic, shifted its attention to humans, renewing *P. vivax* transmission[31,34].

All the studies retrieved for the present review are summarized in Table 1, providing information on the effect on mosquito population dynamics and malaria transmission of each WDP.

CONTROL IN WATER DEVELOPMENT PROJECTS

In order to select an appropriate location to implement a WDP, research on the following factors is encouraged; i) bionomics of local anopheline species, ii) characteristics of the communities that will be placed under the influence of the WDP, iii) environmental variables that may modulate malaria transmission and iv) the capacity of the local health system to respond efficiently to risk situations. This knowledge would also allow control programmes to forecast the negative effects on health of that project in that specific setting and to prepare adequate palliative measures to be implemented[8]. For example, different social groups such as dam workers, dislocated people or traditional tribes may present different susceptibility to health hazards that need to be considered when planning an integrated control program[70,83]. To tackle the negative health outcomes, several strategies of environmental management, biological and chemical control methods and population education approaches may be considered for controlling malaria in WDP.

Insecticide resistance of malaria vectors due to the massive use of chemical compounds in agriculture and public health can hinder control programmes. A prime example of insecticidal resistance due only to agricultural applications was found in some *An. albimanus* populations of El Salvador[27]. This was confirmed because resistance levels were higher in mosquito populations close to the paddy fields (space correlation), also higher resistance levels were observed during the spraying periods of ricefields (time correlation) and because the agricultural insecticides were less efficient to control *Anopheles* populations than in previous years[27,57]. In Sri Lanka, resistance due to agricultural pesticides was observed also in *An. nigerrimus* populations. However, *An. culicifacies* B developed resistance due to public health campaigns in the same country. This was explained for the different vector ecology and exposure to the different insecticidal compounds. *An. culicifacies* B rest mainly indoors entering in contact with the insecticides used for Indoor Residual Spraying (IRS), while *An. nigerrimus* rest principally outdoors and their larvae are largely found in ricefields were the pesticides for agriculture are applied, encountering also resistance in the immature stages[39,57].

Impregnated bednets have been proven a very useful tool for reducing human-vector contact rate, thus reducing considerably malaria transmission in many areas and settings[69]. In areas under the influence of two dams in the Senegal River, a reduction of 90% of malaria prevalence was observed in treated communities with impregnated bednets. Their use also proved efficient in the control of infection in the Tigray region of Ethiopia[13,29]. Conversely, bednets were not successful for controlling malaria in the proximities of the Bargi dam in India. This area is inhabited by ancestral tribes with specific socio-cultural characteristics which impeded the proper implantation of the bednets[82]. Large number of mosquitoes produced in flooded fields may represent an intolerable biting rate for irrigation communities, so many households will start to use bednets in a higher rate than neighbouring non-irrigated areas. This situation has been reported in irrigated villages in The Gambia, Cameroon and Burkina Faso. High bednet coverage may explain to some extent why malaria incidence is kept to moderate levels in such irrigated villages with elevated mosquito densities[44].

Alternative methods to mitigate the malaria burden are IRS and the use of impregnated curtains in windows and repellents. At the Uttaranchal dam in India, a better socioeconomic status and knowledge of the risk factors for malaria of the settlers close to the project, plus sound vector control measures such as IRS, abolished the disease transmission in at risk communities[49]. In Thailand, sound integrated control measures averted

Table 1

Summary of studies on the impact of water development projects (WDP) on anopheline bionomics and malaria transmission

Continent/country	Type of WDP	Main malaria vectors	Effect on anopheline bionomics *	Effect on malaria transmission **
África				
Burkina Faso	Irrigation scheme	*An. gambiae s.l*	ID	RT (high use of bednets)
Burundi	Rusizi ricefields	*An. arabiensis*	ID	IT of *P. falciparum*
Cameroon	Logone ricefields	*An. gambiae s.s,* *An. arabiensis*	ID	IT
Ethiopia	Tigray micro-dams	*An. arabiensis*	ID	IT
	Gilgel-Gibe dam	*An. gambiae s.l*	ID	IT of *P. vivax*
	Koka dam	*An. pharoensis,* *An. arabiensis, An. funestus*	ID	IT
Gambia	Irrigation scheme	*An. gambiae s.s,* *An. arabiensis*	ID	NT in the dry season
Ivory Coast	Irrigation scheme	*An. gambiae s.l*	ID	NT (better socio-economic conditions)
Kenya	Mwea ricefields	*An. gambiae s.l,* *An. pharoensis*	ID	IT
	Ahero ricefields	*An. arabiensis, An. funestus*	ID	NT (Effective IRS)
Madagascar	Highlands ricefields	*An. funestus*	ID	IT (*P.falciparum* epidemics)
	Southern ricefields	*An. funestus,* *An. mascarensis*	ID	IT in arid and NT in humid areas
Mali	Sahelian ricefields	*An. gambiae s.s*	ID	IT in dry season and RT in rainy season
Senegal	Diama dam	*An. pharoensis,* *An. gambiae s.l,* *An. funestus*	ID of *An. pharoensis* and *An. funestus*	NT (high coverage of bednets)
	Irrigation scheme	*An. pharoensis*	ID	NT
Sudan	Gezira ricefields	*An. arabiensis*	ID	IT at the beginning, RT after efficient malaria control
Tanzania	Irrigation scheme	*An. arabiensis*	ID	RT (bednets, prompt and efficient treatment, screened windows)
Asia and the Pacific				
Afghanistan	Irrigation scheme	*An. pulcherrimus,* *An. hyrcanus*	ID	IT
Bangladesh	Lowland dams	*An. philippinensis*	RD	RT
China	Irrigation scheme	*An. sinensis*	ID	IT
India	Uttaranchal dam	*An. culicifacies,* *An. fluviatilis*	RD	RT (efficient control and better socio-economic conditions)
	Bargi dam	*An. culicifacies,* *An. fluviatilis*	RD *An. culicifacies* and ID of *An. fluviatilis*	IT and increased proportion of *P.falciparum* infections
	Micro-dams	*An. fluviatilis,* *An. culicifacies*	RD	RT
	Thar Desert ricefields	*An. culicifacies,* *An. stephensi*	ID	IT and predominance of *P. falciparum*
	Narmada ricefields	*An. culicifacies,* *An. fluviatilis*	ID	IT
Indonesia	Coastal ricefields	*An. campestris*	ID	IT
	Irrigation scheme	*An. barbitorsis,* *An. aconitus*	ID	IT
Laos PDR	Irrigation scheme	*An. nivipes*	ID	IT

Table 1
Summary of studies on the impact of water development projects (WDP) on anopheline bionomics and malaria transmission.(cont.)

Continent/country	Type of WDP	Main malaria vectors	Effect on anopheline bionomics *	Effect on malaria transmission **
Asia and the Pacific				
Nepal	Irrigation scheme	*An. culicifacies* A	ID	IT
Sri Lanka	Mahaweli ricefields	*An. annularis, An. subpictus* *An. culicifacies* B	ID *An. annularis* and RD *An. culicifacies* B	IT at the beginning, RT (IRS and prompt and effective treatment)
Thailand	Srinagarind dam	*An. minimus,* *An. balabacensis,* *An. maculatus*	ID	IT
Turkey	Irrigation scheme	*An. sacharovi*	ID	IT, *P. vivax* epidemics
Latin America				
Brazil	Balbina dam	*An. nuneztovari*	ID	NT (efficient malaria control)
	Samuel dam	*Anopheles sp*	ID	IT
	Tucurui dam	*An. nuneztovari,* *An. braziliensis*	ID	IT
	Itaipu dam	*An. darlingi,* *An. albitarsis s.l,* *An. galvaoi*	ID	IT
	Serra da Mesa dam	*An. darlingi*	ID	IT
	Taquaruçu dam	*An. albitarsis s.l,* *An. darlingi*	ID	No malaria transmission
	Porto Primavera dam	*An. darlingi*	ID	No malaria transmission
	Rosal dam	*An. albitarsis*	ID	No malaria transmission
	Igarapava dam	*An. darlingi,* *An. albitarsis s.l*	ID	No malaria transmission
	Peixe Angical dam	*An. darlingi,* *An. albitarsis s.l,* *An. triannulatus*	ID	No malaria transmission
	Jari irrigation scheme	*An. darlingi*	ID	IT
	North Amazon agricultural settlement	*An. darlingi*	ID	IT
	Southeast ricefields	*An. albitarsis s.l*	ID	No malaria transmission
British Guyenne	Irrigation scheme	*An. aquasalis*	BC	IT. *P. vivax* epidemic
Central America	Irrigation scheme	*An. albimanus*	ID	IT
Peru	Irrigation scheme	*An. albimanus,* *An. pseudopunctipennis*	ID	IT
Suriname	Brokopondo dam	*An. darlingi* *An. nuneztovari*	ID of *An. nuneztovari*	

*ID - Increased Densities, RD - Reduced Densities , BC - Behaviour Change. ** IT - Increased Transmission, RT - Reduced Transmission, NT - No Transmission modification

the increase on malaria incidence in adjacent areas of the Ubolratana dam[85]. Another example in this region comes from Laos PDR, were epidemiological surveys demonstrated that control measures efficiently reduced the endemicity at a very low degree in areas close to an artificial lake in the Keoudum district[30]. It is important to bear in mind that pressure due to control measures may affect the behaviour of malaria vectors. This phenomenon was observed at the Tucurui dam in Brazil, where the local *An. darlingi* population shifted to a more exophilic behaviour due to the pressure of control measures such as IRS and impregnated curtains, coupled with a change in human behaviour[87].

To overcome insecticide resistance problems, environmental management and biological agents for malaria control have been highlighted. It is important to know the bionomics of all potential malaria vectors of a specific area when applying environmental management strategies, as a specific intervention may deter a species to colonize the site but may benefit the adaptation of another local species with a different vector capacity[93]. Environmental manipulation consists in actions that produce temporary conditions that are unfavourable for mosquito proliferation in WDP. All these control methods may be used along the different parts of a WDP, from the artificial lake that stores the water for its distribution and energy production to the drainage systems, passing through the distribution canals and paddy fields[97,98]. For example, if irrigation canals are lined in order to avoid the formation of standing water bodies, with proper edge maintenance and vegetation removal, a reduction of potential breeding sites may be achieved[99]. This was observed between well planned and unplanned ricefields in the irrigation scheme of Mwea in Kenya. Larval densities were higher in the unplanned rice growing villages as their canals and flooded fields were not properly drained, providing more opportunities for *Anopheles* to breed[62].

An easy and effective strategy to reduce negative health impacts is to establish these WDP far enough from the communities, so that they are out of the flight range of the local anopheline species[29]. The filling of a reservoir will cover several isolated natural breeding sites in a determined area, although an extensive new shoreline may be used for the Anophelinae to breed. So, a more extensive area that can become a potential breeding site will be defined, but this area would be easier to identify and control than the sparse natural water bodies[98]. In some South American ecosystems, like the "cerrado" and "caatinga", the implementation of irrigated schemes may reduce the sources of breeding, decreasing in turn the anopheline densities and malaria transmission[70]. Community participation may enhance control programs in WDP, as was proved in the Tigray area of Ethiopia, where local communities and health workers were implicated in the filling or drainage of potential breeding sites[102].

For efficient malaria control in man-made lakes, another strategy for mosquito population abatement is to fluctuate periodically the lake water levels and hence alter the flight range of local *Anopheles*. For example, during the dry season, reservoir capacity may be lowered considerably and the area under the flight range of mosquitoes may be considerably curtailed, placing some communities at less risk of acquiring the disease[49]. Nevertheless, this control strategy must be carefully planned, as it was observed that, when the Samuel dam in Brazil naturally reduced its water levels during the dry season, malaria incidence and *Anopheles* populations were exacerbated due to the exposure of new areas of land with stagnant water[79]. The efficiency of fluctuating reservoir water levels also depends on the correct maintenance of the banks, mainly reducing the amount of associated vegetation that may facilitate some mosquitoes to breed. One of the first examples of the success of fluctuating water levels and the removal of vegetation from the lake edge for anopheline control comes from the dams at the Hales Bar and Falling Water rivers in the U.S.A., where *An. quadrimaculatus* was responsible for severe epidemics[95]. GUIMARÃES *et al.*[36] conducted an analysis between the lake's shoreline characteristics and water level fluctuations and variations in mosquito populations in the Serra da Mesa Brazilian reservoir. Keeping 10 meters above the shoreline free of vegetation was argued to be a key factor to avoid the proliferation of *Anopheles* sp. during the first stage of the WDP, and especially for *An. darlingi* that cannot breed in totally exposed sites. Anophelinae densities were highly correlated with the fluctuation of dam water level, increasing when water contacted the surrounding vegetation. This phenomenon was also reported from the Peixe Angical dam in Brazil, where the highest number of *An. darlingi* were recorded when the reservoir was being filled, as this process was accompanied by increased decomposition of vegetation along the banks and greater shading of the reservoir margins[78]. Variations in reservoir water level also impeded the maintenance of proper breeding sites of *An.darlingi* at the Lages dam in Brazil, thereby substantially curtailing human exposure[41]. Periodic discharges from the reservoir may reduce breeding in water distribution channels and other areas downstream[98,99]. This last strategy probed to be useful to maintain at low levels *An. culicifacies* populations in downstream areas of a WDP in Sri Lanka[53].

Intermittent irrigation is a classic and very efficient method to control mosquito populations in paddy fields, consisting of repetitive dry stages of the crops, not allowing the water to be on the cultures for more time than the larval development of the anophelines. This approach may also increase crop productivity. Depending mainly on temperature (larvae development is faster in the tropics) and also in each specie's biology, the time estimated from when the egg is laid until the complete development of the adult mosquito may be around 18 days[50]. Another factor to consider is the time that anopheline eggs may stay viable in the dried fields. For example, eggs of *An. sinensis* may resist for three days without water in soils with a minimum of 90% of humidity. Intermittently irrigated ricefields may be implemented in areas with enough water availability and without high rainfall patterns[59]. Positive experiences reducing malaria incidence due to intermittent irrigation are reported from the Senjayakollai area in India (reduction of parasite rates from 42% to 0%) and in China, where malaria prevalence declined due to a fall of 84-86% of the *An. sinensis* larvae populations. Intermittent irrigation and insecticides may reduce the population of mosquito predators present in the paddy fields, which in some cases may exert high pressure to maintain mosquito densities at low levels[50,72].

Some study cases have shown that very high mosquito densities may reduce the longevity of the vector, thus mitigating malaria transmission. Based on this observation, malaria transmission could be controlled by synchronizing all the paddy fields of an area in order that only a small proportion or most of them are in the same developmental stage. During rainy season, an increased mosquito production of paddy fields may produce such high mosquito densities that anopheline longevity may be reduced. Also, it is easier to implement focalised control measures if only some ricefields are operated around determined irrigation communities[19].

There are many examples of the use of biological methods to abate *Anopheles* populations in ricefields. The main strategies are using fish as predators, microbial agents such as *Bacillus thuringiensis* var. *israelensis* and *B. sphaericus* and nematodes that can parasite mosquitoes such as *Romanomermis culicivorax*[54]. For example, the use in China of larvivorious fish was seen to be useful to reduce mosquito populations in paddy fields, helped in the fertilization of the crops and also provided with extra 50 kg of fish for each 15 hectares of cultivated rice to the local population[98].

Geographic Information Systems (GIS) and spatial analysis have been increasingly used in recent years for the study and control of vector-borne diseases[64]. This tool can assist us in the prediction of epidemiological risk situations and they have proved to be of great applicability in areas under the influence of a WDP. A first example comes from Mali, where a GIS was used to evaluate if paddy fields mapped with remote systems, could explain the variations of mosquito densities among some communities. The authors highlighted that the water management of irrigated fields was the most influential factor that modulated the mosquito population dynamics[19].

LAUTZE *et al.*[55] concluded using a GIS that the distance of the communities to the Koka reservoir in Ethiopia was one of the variables more highly correlated with malaria incidence. They verified that communities placed in a distance of 0-3 km, 3-6 km and 6-9 km from the lake shoreline presented infection rates per 1000 people/month of 6.74, 4.60 and 2.91 respectively. This difference in malaria exposure is related to the decreasing gradation of vector densities that is normally established from the WDP margins. For example, 17 bites/person/night by *An. gambiae s.l* were recorded in the margins of an irrigated scheme in Senegal. This index dropped to one bite/person/night in areas located at 5 km[20].

In the Amazonian region, VITTOR *et al.*[94] applied GIS to analyze the impact of different land use in the Peruvian Amazon and to predict variations in *An. darlingi* distributions and densities. They concluded that the EIR was gradually increased in areas with a higher proportion of grass/crop land. Another example is provided by ZEILHOFER *et al.*[103] who used GIS at the Manso dam, Brazil, to model the suitable breeding site habitats for *An. darlingi*. Environmental and climatic factors such as temperature, humidity, rainfall, distance to potential breeding sites, topography and lake border vegetation cover, were correlated with the spatial and temporal distribution of this vector. This analysis allowed the generation of a detailed map of the dam area, highlighting the most favourable spots for *An. darlingi* to breed.

DISCUSSION

It is estimated that by year 2025, a total of 9,4 billion people should have their food and energetic demands covered. As a result it is expected that irrigation schemes and dams will be extensively expanded mainly in the tropics. For this reason, if sound prevention measures are not properly implemented, a global health deterioration related to these WDP may be anticipated[50].

We have reviewed several studies that assessed the effect of dams and irrigation on *Anopheles* bionomics and malaria epidemiology, defining diverse situations, such as increased vector densities accompanied by increased, decreased or no changes in malaria transmission, decreased vector densities, ecological succession of mosquito fauna and vector behaviour modifications.

When population movements introduce new *Plasmodium* parasites in free or under control malaria areas, several factors such as human population densities and acquired immunity levels, climate, available prevention and control measures and very importantly, the presence of an efficient vector in enough numbers, will determine if a new transmission focus will be established[35]. The establishment of a new malaria foci has been well documented in areas under WDP influence of Africa (i.e: Gilgel-Gibe dam in Ethiopia and several sub-Saharan irrigation schemes), Asia and the Pacific (i.e: Bargi dam and Thar Desert ricefields in India and Srinagaring dam in Thailand) and the Americas (i.e: Serra da Mesa and Itaipu dams in Brazil)[22,36,37,40,88,99].

Each anopheline species has its own optimal breeding requirements, such as sun level exposure, water turbidity and temperature, current, presence of associated vegetation, pH and organic matter concentration. For this reason, not all WDP will provide optimum breeding grounds for the local malaria vectors[49]. Usually species with preference for exposed breeding sites thrive more efficiently in man-made lakes. For example, *An. arabiensis* has a preference for open sunlit breeding sites with few associated vegetation and a certain degree of turbidity[35]. This species thrived in some WDP that presented such conditions, like the Koka dam and the micro-dams of the Tigray region, both in Ethiopia. *An. nuneztovari* has also preference for natural sun exposed breeding sites, such as pools, slow flow streams, lakes and animal footprints. This vector has been found breeding efficiently in many man-made lakes such as de Balbina and Tucurui dams in Brazil and the Brokopondo dam in Suriname, inclusive displacing other anopheline species and developing resistance to insecticides[87,88]. At the Tucurui dam, an increase from 25.6 to 53.3 mosquito bites/person/hour were registered and the biting activity peak of the anophelines was advanced to 18:00 due to the enormous proliferation of *Mansonia* sp populations, also well adapted to the new environmental conditions[70,88]. Moreover, proliferation of the less sun-loving *An. darlingi* in dams is observed when project margins are associated with vegetation that creates appropriate breeding conditions for this species. This has been reported from the Itaipu, Serra da Mesa and Manso dams in Brazil. From South America, also *An. albitarsis s.l* has been several times associated with man-made lakes or irrigation projects. *An. culicifacies*, a primary malaria vector in most of the Asian continent, shows low adaptability to irrigated areas. This vector tends to disappear from rice cultivations when the crops reach 76 cm but it can be abundant in water distribution canals and spillages of the WDP[75]. *An. culicifacies* is a complex of species. In Sri Lanka *An. culicifacies* B is predominant and it has few adaptability to flooded ricefields[51]. In contrast, *An. culicifacies* A has showed better potential to colonize this environment in Nepal, increasing malaria transmission[100]. Other Asiatic primary malaria vectors such as *An. fluviatilis, An. stephensi, An. minimus* and *An. dirus* are not good colonizers of paddy fields. On the other hand, secondary vectors with more limited potential for malaria transmission such as *An. annularis*, *An. varuna* and *An. jeyporiensis* are well adapted to these artificial settings[75].

The majority of *Anopheles* species have a great potential to colonize and exploit new water bodies. The flight range of most of anopheline mosquitoes between breeding sites and blood meal points varies between 1.5 and 2 km. However, sporadic migratory movements assisted by winds may extend this flight range up to 50 km[99]. Other studies proved that *An. gambiae* can fly longer distance from irrigated fields during the dry season[19]. Due to this high adaptability and mobility capabilities, if a malaria vector is present in an area of a WDP implantation, it may eventually colonize it. There are diverse examples of colonization of new areas by different anopheline species. *An. braziliensis* colonized the Tucurui dam area in Brazil five years after the filling of the reservoir and *An. culicifacies*, a vector absent in the area of the Thar Desert in India, used the new implanted irrigation schemes as new breeding sites to colonize the region[92]. As a result of WDP in Egypt, *An. gambiae* invaded the new areas from Sudan, provoking severe epidemics with almost 130,000 deaths between 1942 and 1943[43].

When determining if anopheline species will successfully adapt and proliferate in WDP, climatic and other biotic and abiotic factors may play an important role. For example, in the Amazon exists three types of rivers (white, black and clear water rivers) which differ in parameters such as the pH, concentration of organic matter, sediments and associated vegetation. The differential effect on the mosquito populations of the different dams in the Amazon will be determined to some extent for the type of river dammed. For instance, macrofits proliferation (such as *Pistia stratiotes* and *Echhornia crassipes*) is well sustained in white water rivers

(Tucurui dam) and not in black water rivers. These macrofits have been associated with an increased production of the main malaria vector of the Amazon, *An. darlingi*[65].

Temperature and rainfall are the two main climatic factors that have influence on malaria transmission. The later determines the number of potential breeding sites and hence, vector densities, while the former ascertains the duration of the larval development and the sporogonic cycle inside the mosquito[61]. GUIMARÃES *et al.*[37] pointed out that in the area under the influence of the Itaipu dam, rainfall did not pose a direct influence on mosquito densities, as the reservoir experienced few water level fluctuations, thus remaining a stable breeding site independent from the rain patterns. In contrast, another report from the Peixe Angical dam in Brazil, demonstrated that climatic factors played an important role, as greater rainfall influenced negatively on the abundance of *An. albitarsis s.l* and *An. triannulatus s.l.* In addition, higher temperatures were related with increased numbers of *An. albitarsis s.l* at the dam site[78]. Another example of the key role of climatic factors in man-made environments is found in a sahelian area of the Gambia, where malaria transmission is intense during the rainy season and very limited during the drier months. The introduction of irrigated schemes in this setting offered new potential breeding sites for local malaria vectors. This resulted in another peak of high mosquito densities during the dry months but, surprisingly, without an increase in malaria incidence. The extreme temperatures of 42.7 ^{o}C in the shadow and the very low relative humidity affected the adult mosquito survival rates. In addition, there are some evidences that the extreme temperatures may be also lethal for the *Plasmodium* parasites, impairing also their development inside the *Anopheles*. This was a case of “Anophelism without malaria”[56].

Almost 25% of the known species of *Anopheles* that can transmit malaria can thrive in ricefields. Different anopheline species will predominate in different rice crop stages and the mosquito densities are lower when the crops are very tall as the mosquito females find more difficult to reach the water of the paddy fields to lay their eggs[100]. Other factors that may influence mosquito productivity are water depth, duration of flooded periods, growing rate of the crops and the extension area under cultivation[50].

This succession of Anopheles species during the different crop developmental stages has been well documented. For example, in Africa, *An. gambiae s.s* and *An. arabiensis* are more abundant during the early crop stages as they prefer to breed in sun exposed water bodies. *An. funestus* can be found in higher abundances during later crop stages, as it presents preference for shaded or semi-shaded breeding sites[73]. In other continents, this alternation on anopheline species also occurs. Sun-loving species such as *An. albimanus* (America), *An. fluviatilis* and *An. culicifacies* (Asia) are considered pioneer species in the colonizing of paddy fields, while species that prefer less exposed breeding sites are *An. punctimacula* (America) and *An. umbrosus*, *An. hyrcanus* and *An. leucosphyrus* (Asia)[73]. This succession of species was also observed in some dams of the Senegal River where *An. gambiae s.s* and *An. arabiensis* were the most abundant species before the dam construction, but *An. pharoensis* became the predominant species when the project was completed, accounting for most of the new malaria infections. The Diama dam also provoked an interruption of the flux of the sea salt upstream the Senegal River, allowing the colonization of the area by *An. funestus*[18,80]. This ecological succession of species in WDP has important epidemiological significance, as each species has its own vector capacity.

From all cited above, it is important to evaluate the potential health hazards following a holistic and multidisciplinary approach during the design, construction and operation of WDP. Effective control methods have been proved effective in such settings. Active case detection and prompt and effective treatment of infected individuals coming to WDP areas, good maintenance of lake margins coupled with sound water level management, and classic vector control methods such as IRS, the use of impregnated bednets and larval control would be encouraged to tackle malaria in these scenarios. It would be advised to conduct additional site-specific studies in endemic areas (if possible collecting pre- and post-intervention data and using consistently, informative parameters such as the EIR) under the direct effect of dams and irrigation schemes, in order to increase our knowledge on this topic and improve our approaches to minimize the negative health effects of these human interventions. We also consider GIS technologies a tool with a high potential to assist on the study and control of malaria in such scenarios, and its use should be further explored.

RESUMO

Impacto de hidrelétricas e campos de irrigação na bionomia dos anofelinos (Diptera:Culicidae) e na epidemiologia da malária

Intervenções humanas como projetos de irrigação e usinas hidrelétricas, tem se transformado em graves problemas de saúde em muitos países, especialmente naqueles localizados nos trópicos. No presente artigo discutimos os efeitos que essas intervenções causam a dinâmica populacional dos anofelinos e nos padrões de transmissão de malaria. Foram revisados estudos feitos nas três principais regiões geográficas dos trópicos e sub-trópicos (África, Ásia e o Pacífico e Américas). Constatamos que os padrões da transmissão da malária antes da introdução dos empreendimentos, as medidas de controle, os movimentos demográficos, os padrões comportamentais das comunidades humanas e a bionomia dos anofelinos locais determinarão se o estabelecimento de campos de irrigação e/ou usinas hidrelétricas podem influenciar negativamente na saúde das pessoas. São apresentados exemplos de medidas de controle bem sucedidas nesses cenários. A utilização de *Sistemas de Informação Geográfico* tem sido destacada como uma importante ferramenta para subsidiar o estudo e controle da malária em áreas sob impacto ambiental.

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Received: 17 February 2011
Accepted: 13 April 2012

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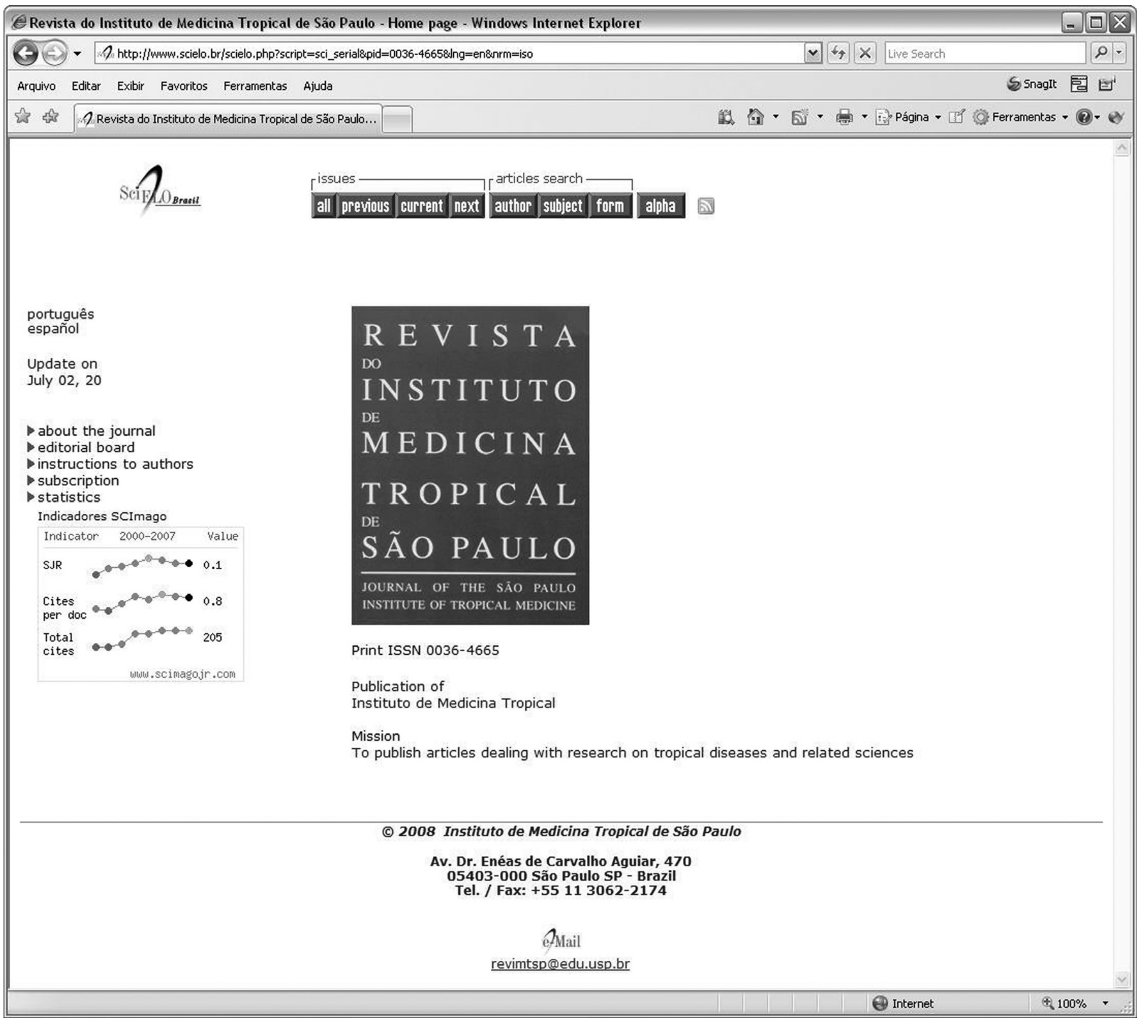

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